EASTMAN KODAK COMPANY
Apparatus and Optical Division
Rochester, New York

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Project: Any Project Requiring the Detection of Image Motion

Subject: Image Motion Detection (V/H Used as an Example)

INTRODUCTION

A V/H sensor which operates on a terrestrial scene may be achieved by various methods. The method we are concerned with here involves scanning an image of the scene with a bar reticle and using the signal derived from the scan to maintain the image fixed with a position servo. The position servo can drive a table containing the sensor objective and thereby maintain the LOS fixed with respect to the scene; if the camera is mounted on the same table IMC is provided for the camera. Alternatively, optical elements in the sensor may be driven to keep the image fixed and from the drive information may be extracted to provide IMC data for the camera by the use of a regulator in the camera system.

It is the purpose of this memo to discuss the scene information, the scanning, and, in a preliminary fashion, the optical head.

DISCUSSION

The Scene and Its Image

The detail and contrast in the image of the scene will depend upon both the scene and the optical system. Of interest to the V/H sensor is the power spectrum associated with the spatial frequencies in the image. The power spectrum is readily obtained through the Fourier Transform of the autocorrelation function; the autocorrelation function is easily obtained experimentally with photographic negatives of aerial scenes. These negatives can be generated in the laboratory under simulated conditions.

The power spectrum (or frequency distribution of the energy) will be of the form shown in eq. (1):

$$p(\omega_x) = p_o \delta(\omega_x) + p_n(\omega_x) \qquad (1)$$

The impulsive function accounts for the power transmitted by an image with no information in it. We are primarily interested in $p_n(\omega_x)$; i.e., in the

Spectrum of the information content of the image. The subscript x associated with ω is a reminder that spatial frequencies are the subject of interest.

Suppose that we designate by $\tilde{\tau}_o$ some measure of the "width" of the autocorrelation function of the image. If the image has a dimension L in the direction in which the correlation function is measured, there will be approximately $L/\tilde{\tau}_o$ independent sampling points in the field; an upper limit on the number of bars in the reticle associated with the field L is established by this relationship.

The Scanning System

We will study the scanning of an image with a bar reticle of 50/50 composition as shown in figure 1.

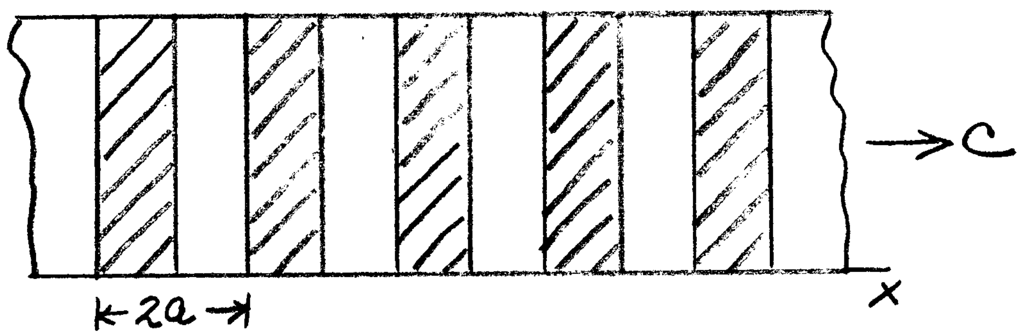

Figure 1

Let the spatial period of the bars be 2a and let the reticle move at a velocity c in the x direction. The spatial frequency is 1/2a and the temporal frequency is c/2a.

If a condensing system collects the chopped light from the fixed scene and transmits it to a phototube an electrical signal of period $T = 2a/c$ will be generated. We seek the amplitude and spectral composition of this temporal signal as it relates to the scene.

The scanning function $S(x,t)$ is:

$$
\begin{aligned}
S(x-ct,\ a) &= 1;\ o < (x-ct) < a \\
&= 0;\ a < (x-ct) < 2a \\
S(x-ct, a) &= S(x-ct + 2a,\ a)
\end{aligned}
\qquad (2)
$$

i.e., the spatial period is 2a, the temporal period is 2a/c as indicated before; the transmission of the reticle bars is zero, the transmission of the interstices is unity, figure 2.

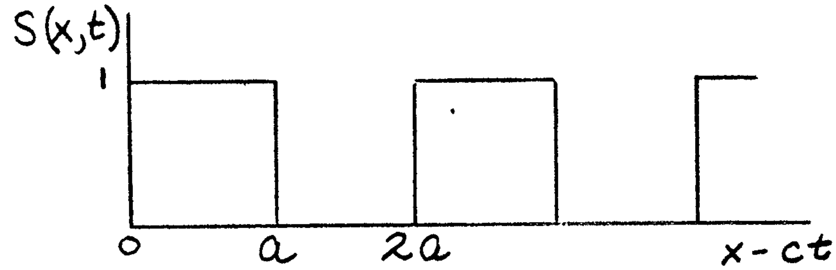

Figure 2

As far as the reticle is concerned, the light in the image is a function of x only. Denote the light intensity by $I(x)$. Then the flux falling on the phototube is:

$$F(t) = \int_0^L I(x)\, S(x,t)\, dx \qquad (3)$$

where L is the dimension of the reticle in the x direction. With no loss of generality we may take $a = \pi$ and write the Fourier series for $S(x,t)$:

$$S(x,t) = 4/\pi \left[\sin (x-ct) - 1/3 \sin 3(x-ct) + \text{---}\right] \qquad (4)$$

and

$$F(t) = \int_0^L 4/\pi \; I(x) \left[\sin (x-ct) - 1/3 \sin 3(x-ct) + 1/5 \sin 5(x-ct) \text{----}\right] dx \qquad (5)$$

Because of the orthogonal properties of the trigonometric functions, the reticle tends to select from the scene those spatial frequencies corresponding to the spatial frequency of the reticle bars and the odd harmonics of this frequency.

However, the orthogonality conditions, (i.e., that the spatial frequencies of the scene and the reticle be commensurable and also that the integration extend over the least common period of the two) are not satisfied by all frequencies in the scene. We seek the contribution to the amplitude of $F(t)$ of all the frequencies in the scene. In particular, we seek the fundamental frequency component of $F(t)$ generated by the first term of the series (4).

$$F_1(t) = 4/\pi \int_0^{2\pi N} I(x) \sin (x-ct)\, dx \qquad (6)$$

Let[1] $$I_n(x) = \sum_n \left(a_n \cos f_{nx}x + b_n \sin f_{nx}x\right) \tag{7}$$

where a_n and b_n are independent random variables distributed about the mean in such a way that

$$p_n\,(f_n)\,\Delta f = \overline{a_n^2} + \overline{b_n^2} \tag{8}$$

furthermore, that

$$f_n = n\Delta f \tag{9}$$

and the standard deviation of the a_n and b_n is $\sqrt{p_n(f_n)\,\Delta f}$. (Note that f_{nx} is used in (7) rather than ω_{nx} to be compatible with the previous choice of $2a = 2\pi$.)

Let us first evaluate

$$F_{1b} = 4/\pi \int_0^{2\pi N} b_n \sin f_{nx}\, x \begin{bmatrix} \sin x \cos ct \\ -\cos x \sin ct \end{bmatrix} dx \tag{10}$$

then

$$F_{1b} = 4b_n/\pi \left[\left(\frac{\sin\,(f_{nx} - 1)x}{2(f_{nx} - 1)} - \frac{\sin\,(f_{nx} + 1)x}{2(f_{nx} + 1)} \right) \cos ct + \left(\frac{\cos\,(f_{nx} - 1)x}{2(f_{nx} - 1)} + \frac{\cos\,(f_{nx} + 1)x}{2(f_{nx} + 1)} \right) \sin ct \right]_0^{2\pi N} \tag{11}$$

(The apparent singularity in $\dfrac{\cos\,(f_{nx} - 1)x}{2(f_{nx} - 1)}$ at $f_{nx} = 1$ is nonexistent as can be seen by examination of the integrand in (10)). Compared to the first term of (11) the others are negligible, therefore

$$F_{1b} = 4b_n/\pi \; \frac{\sin\,(f_{nx}-1)\,2\pi N}{2(f_{nx}-1)} \cos ct \tag{12}$$

This equation shows that the flux is sinusoidal in time with frequency $c/2\pi$ and with amplitude

$$A_b = 4b_n N \frac{\sin y}{y} \tag{13}$$

where each change of 2π in y represents a unit change of pitch in the spatial frequency of the scene relative to the reticle spatial frequency. For y equal

1. Mathematical analysis of Random Noise, Rice, BSTJ Vols. 23 and 24

to integral multiples of π (orthogonality) there is no contribution to the flux.

Secondary maxima of $\frac{\sin y}{y}$ occur approximately at $y = K\,\pi/2$; ($K = 3, 5, 7, ---$), the amplitudes of these approximate maxima are $2/K\pi$. (Note that $2/\pi$ is the amplitude at $y = \pi/2$ and provides a convenient "half power point" reference, the "Q" is of the order of N).

We state without proof that the integration in (7) involving the cosine terms results in the same amplitude function but the temporal function is sinusoidal rather than cosinusoidal. Then:

$$F_1(t) = 4N \sum_n \left(a_n \frac{\sin y}{y} \sin ct + b_n \frac{\sin y}{y} \cos ct\right) \qquad (14)$$

where

$$y = 2\pi N\,(f_{nx}-1)$$

<u>The Electrical Signal</u>

The phototube converts light energy into electrical current so that, within a transducer scale factor, eq. (14) describes the fundamental component of the electrical current:

$$i_{s1}(t) = F_1(t) \times K_p \qquad (15)$$

From these discussions we see that the signal power depends directly on the scene spectral power in the spatial frequency region near the reticle spatial frequency. (A rough estimate shows that 90% of the total signal power will be derived from the "main lobe" of the scanning function.)

This result is both good and bad. Spatial discrimination is possible but if the scene contains no spatial frequencies in the region of the reticle spatial frequency, there will be no signal power.

Since both spatial and temporal frequencies depend upon reticle spatial frequencies, it is quite possible to have several reticle frequencies and sort out the scene spatial content on the several temporal "carrier" frequencies.

The temporal spectrum will consist of the fundamental and odd harmonics in accordance with eq. (5). If the reticle spatial frequency is chosen near the upper limit of the scene spatial frequencies, the power in the odd harmonics of the temporal frequency should be negligible.

The possibilities for a phase locked servo appear to be excellent. According to eq. (14) the phase for a particular scene will depend on the ratio $\sum_n a_n / \sum_n b_n$. Small shifts in the time reference due to image motion will introduce a corresponding shift in phase.

Velocity Discrimination

If a portion of the format moves with respect to the fixed image, the temporal signal for this portion will have the form:

$$i_s = A \cos (c \pm \Delta c)t$$

This signal will be shifted in temporal frequency by $\frac{\pm \Delta c}{2a}$ from the fundamental signal at frequency c/2a. If the moving (cloud) object has spatial frequency characteristics which permit a degree of spatial discrimination that reduces the power in its associated spectral line below the power of that due to the terrestrial format, discrimination can be readily accomplished.

A brief look at the physical characteristics of the scanning system is in order.

A 1" lens has a resolution limit of the order of 2×10^{-5} radians; assume for the sake of an example that this lens is to provide 10^{-4} radians resolution. At f/10 the least circle corresponding to 10^{-4} radians will be 10^{-3} inches and this should be the reticle bar dimension. The depth of focus would be of the order of 10^{-2} inches. A 100 line reticle would require a field of 0.2" or about 1°. If a squirrel cage type cylindrical reticle were used to scan, the required radius of curvature would be of the order of 0.5"; e.g., a 1" diameter cylinder is required. If a temporal frequency of 400 cps is used, the corresponding rotational speed of the rotor would be of the order of 15 rpm. Jitter in the rotor would have to be held to a few seconds of arc at frequencies below 400 cps. Slip would have to be held to less than 0.1%.

Figure 3 presents a preliminary configuration of the sensor scanning head suitable for detecting image translation of a plane image in orthogonal directions.

CONCLUSIONS

(1) A V/H sensor of the type described here has the following potential merits:

(a) The sensor can be used in a sensor-camera position servo mode which will eliminate the need for a measurement of V/H and provide IMC directly.

(b) Spatial discrimination can be accomplished.

(c) Velocity discrimination can be accomplished.

(d) IMC (V/H) may be held to less than 1% on a frequency basis; if phase lack is feasible 0.1% or better is probable.

(e) The sensor is simple and straightforward.

(f) Multiple spatial frequencies in the reticle will provide V/H compatibility for a broad range of scenic content.

(g) The reticle drive is a potential, serious design problem.

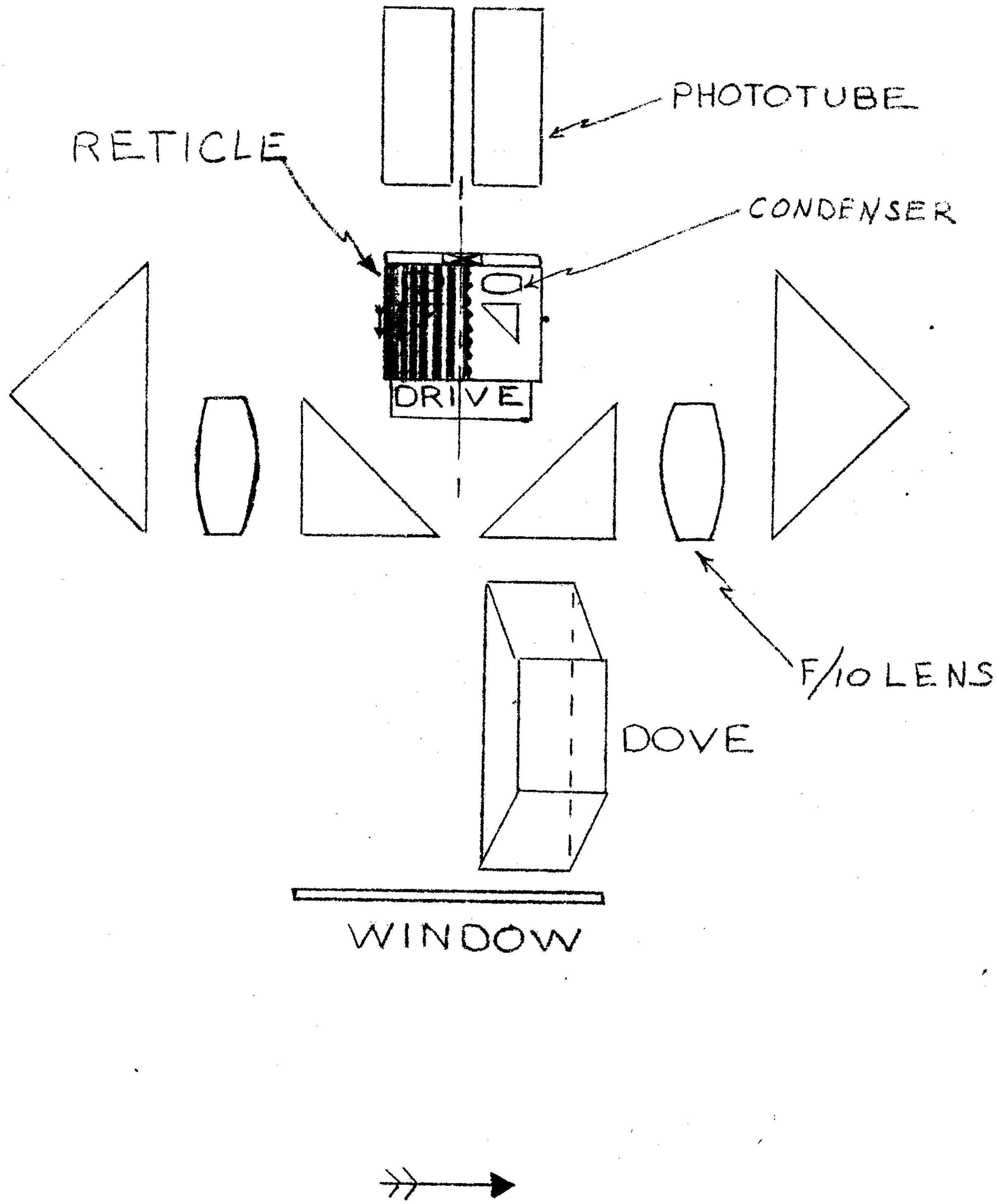

FIG. 3

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